Insulation Coordination for Advanced Rotating Energy Systems: A Preliminary Assessment

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Electromagnetic armaments and electric launchers are emerging systems that are of increasing importance to the armed forces. Included in this category are the railgun, coilgun, reconnection gun, electrothermal gun (ET), and electrothermal-chemical gun (ETC). The system design issues for managing electromagnetic fields and insulation systems, which may include compulsators and pulse disk alternators, in the military applications for which they are intended, have been the subject of this study.

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Insulation Coordination for Advanced Rotating Energy Systems – A Preliminary Assessment

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Abstract

Electromagnetic armaments and electric launchers are emerging systems that are of increasing importance to the armed forces. Included in this category are the railgun, coilgun, reconnection gun, electrothermal gun (ET), and electrothermal-chemical gun (ETC). The system design issues for managing electromagnetic fields and insulation coordination issues generated by these devices and their associated pulsed power systems, which may include compulsators and pulse disk alternators, in the military applications for which they are intended, have been the subject of this study.

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Executive Summary

The battlefield of the future will be dominated by a Poynting's Vector flow of a plethora of signals, potentially including direct weapons targeting and fire info/commands/feedback. In this context, the Battlespace Robustness becomes a major one of the links in the chain of supporting the battlefield Commander in effectively achieving his preplanned goal(s). Lack of robustness, especially if not verifiable in real-time, could become catastrophic.

With the advent of major advances in microminiaturization of electronics of all classes, and especially recent novel work by the US, minimization of volumes of interaction as well as interaction lengths through elimination of connectors and cabling all serves to define a viable route to the development of future, more robust electronics for information management.

In addition, the Army is involved in assessing, along with the other services, the utilization of known assets for generation of electromagnetic signals (complex waveforms, pulses, high energy, single shot, high average power - etc) that, if integrated, could be utilized in an ongoing assessment of battlespace robustness.

Recent new initiatives, including the Army Multi-Mission Combat System, will result in highly electrified information management, weaponry, and countermeasures that can be deployed at nearly data-rate speeds in the future battlefield. The utilization of photons and electrons for control, decision making, and weaponry targeting, destruction, and countermeasures for the very first time provides the military with response times far faster than hydraulics, personnel timing, and mobile telecom can achieve.

With this planned advance in mind, Insulation Coordination and Robustness is essential in assuring reliable electronics to attain Battlespace robustness for the US Armed Forces.

The Energy Systems Institute of the State University of New York at Buffalo has completed an initial study for the IAT of Insulation Coordination technical issues for the next generation of rotating machinery, particularly for Flywheel applications. The motorettes whose microdischarge activity at design voltage was evaluated were kindly supplied by CEM as part of the DARPA CHPS program, with permission of M. Freeman, the program manager. Initial evaluation of the entire stator of the Flywheel, developed mainly for design thermal validation, showed microdischarge activity at levels lower than desired, attributable to the necessity of installing metallic thermocouples within the windings. Recommendations are being developed to engage in a somewhat more thorough motorette experimental project in which thermal cycling as well as dc+ac excitation will be applied. In addition, it is necessary to assess the impact of dV/dt repetitive impulsing on the insulation architecture aging for multikilohertz waveforms, which would be needed in these systems. Under development is a new research facility capable of two pulse operation, at up to 100 Hz burst repetition rate that will enable for the first time a definitive understanding of high dV/dt impulse rate of rise effects on cycle life. To date, the motorette results at dc have validated all the design recommendations

developed between the ESI and Bill Brinkman, the insulation expert at CEM. Note that our view is that higher frequency operation could significantly decrease cycle life reliability, as was presented during the ESI briefing at CEM.

In addition, the initial research performed on the motorettes were done in an air environment as opposed to an oil environment based on the primary evaluation that the merits gained by testing in oil would not significantly outweigh those of the open air tests. After some exploration a determination has been made that testing in oil would be a worthwhile endeavor and provide useful information to the IAT.

Summary of Progress

The Energy Systems Institute of the State University of New York at Buffalo is engaged in a preliminary assessment of Insulation Coordination for large rotating machinery. Past experience has clearly shown this is a major potential cause of failure in developmental systems, generally because of extreme operating stresses well beyond the purview of commercial insulation architectures. Because of this observation, the ESI has been supporting the government (previously under ONR support), and now under IAT sponsorship, in understanding reliability validation of modern designs undertaken at CEM.

The preliminary assessment of motorette microdischarge inception and extinction voltages under ac excitation is nearing completion, with some field effects noted that will require careful insulation dielectric constant coordination. Under dc excitation, design voltages were achieved and sustained in motorettes evaluated. Since motorettes are representative of the highest field section of the field windings, they should be applicable to the balance of machine design for flywheel generators of this type. As a check, the complete flywheel stator microdischarge threshold was undertaken at the ESI, with oil dielectric impregnation. Experiments showed that the metallic thermocouple wiring needed to measure thermal performance was limiting the inception voltage levels of microdischarge activity. For this reason dc performance was to design, but ac validation was not reached.

In order to achieve cycle life performance understanding, the preliminary recommendation will be to execute further motorette experiments as a function of temperature and frequency. Under development, with partial IAT support, is a new technique to excite motorettes with high dV/dt pulses at repetition rates up to 2 kilohertz, and rise times to > 100 kilovolts per microsecond. The technique is more than adequate to assess insulation cycle life coordination issues in all classes of rotating machinery. Two pulse evaluation up to 1 MHz has been demonstrated, permitting for the first time direct withstand confirmation in these new insulation systems. Note that both air and dielectric fluid environments should be continued to be evaluated, as the former is a far more convenient quality assurance assembly environment. The intent is to assess development of an insitu monitoring technique to provide, during assembly warning of

incipient failure points. The concept has been validated at the ESI with sufficient sensitivity as to warrant further study.

The ESI report on this insulation quality assessment study is complete. Since this is a complex technical issue, the report is submitted electronically, in Word97, and has been hypertext linked for ease of understanding. In addition, if desired, a Web class *.htm hypertext linked version could also be prepared once final changes desired by the IAT have been accommodated. The reason for this approach is that reediting the latter type of document is time consuming and would be best done only once.

This report contains a section of suggestions on further research on this aspect of machine and high power electronics design that is being globally validated as a major issue of cycle life reliability concern.

Insulation Coordination for Advanced Rotating Energy Systems – A Preliminary Assessment

Background

CEM has been evaluating, in conjunction with this Institute, novel encapsulated Litz magnet wire architectures for advanced rotating energy systems for application to DARPA and U.S. Army systems. The reason has been to try and determine the applicability of these materials and architectures and their robustness to elevated AC+DC conditions. Initial evaluation of motorettes exposed to high electric fields internal to machine, as well as external inverter/pulses in the presence of AC + DC to frequencies of several kilohertz must be understood in order to develop engineering design rules that are fundamentally founded. Erosion and subsequent aging caused by high rates of change of voltage (dV/dt's) must be evaluated and understood. This study is an investigation into the DARPA Combat Hybrid Power System rotating Flywheel insulation coordination. The emphasis has been on evaluation of new insulation architectures and materials, optimized for high temperature (> 100 °C) operation. As all these architectures need quality assurance validation in the normal laboratory environment to enable initial design selection, the emphasis on this present project was insulation coordination in that environment. Further investigations in the insulating dielectric environment of the actual CHPS Flywheel would be appropriate and are recommended in order to develop an understanding of the insulation architecture cycle life to be obtained under actual system use. Such an investigation would now be recommended, based upon the initial results described in this study.

Approach to Assessing and Resolving Any Observed Aging Issues

In order to assess techniques for increasing corona resistance, the desire is to evaluate "motorettes" of the type developed with CEM, as part of the DARPA CHPS program, for evaluation of advanced insulation systems for very high multifactor stress operating conditions.[1], [2], [5], [6] In addition to experimental assessment of microdischarge inception and extinction at AC+DC voltages, thermal changes in these sensitivity levels, and dV/dt impact on microdischarge activity, this work has carried out the initial first assessment in an applied research program to develop a physics based engineering scaling theory. This model is founded on the landmark works of Professor Blaise, the University Professor of the University of Paris, and microdischarge aging theories under development at the ESI.[5] We note that no such information and/or theories exist today to support the system design engineer in the development of ultra high performance rotating energy systems.[1] An insulation system can most practically be evaluated by building "motorettes" with all of the representative insulation system, including the varnish or resin, onboard.

The ESI has developed, with U.S. Industry and government collaboration and support, a unique and very sensitive, microelectric discharge detection technology developed over more than a decade of research. In fact, we have developed a research measurement

capability sufficiently sensitive to measure this microdischarge activity down to what the Bagirov Russian research has substantiated is the fundamental aging threshold. [2]

The ESI has set up these motorettes with the Biddle microdischarge measurement system as well as the new hard tube modulator, the ESI MOD-9, for dV/dt assessment and evaluated relevant insulation system(s) with these research diagnostics that are unique in the world. The Biddle research AC+DC microdischarge detector is capable of measurement of microdischarge activity of real systems down to the Johnson noise threshold. For 400-500 picofarad capacitance systems, this is to less than 0.05 picocoulombs, at a signal to noise ratio of 2. The MOD-9 is a very high dV/dt hard tube modulator based on an early MIT design in the mid-1940's that has been developed into a several hundred ampere peak current pulsed voltage source to 10 – 15 kilovolts, at dV/dt in excess of 100 kV/microsecond. This is much higher than any projected dV/dt limits to be seen by any of EML insulation architectures.

Another issue that the ESI and the CEM have been studying that should be of interest, is the environmental effect on inverter/pulse duty motorette failures from bubble formation during impregnation. Although NONE of the preliminary performance assessment by the ESI has ever shown bubble induced microdischarge activity at room temperatures. The plan was to carry out a preliminary assessment of the robustness of motorettes as a function of temperature and thermal cycling, to further anchor the aging rate of these insulation architectures. The ESI began initial work on investigating the effect of these conditions to support the building of more inverter/pulse resistant systems.

The IAT is supporting this activity at the Institute to perform this work to improve products and lead the industry in inverter/pulse duty compatibility. The appendix provides the reader with a summary of the new preliminary work on insulation robustness of the CEM newly invented insulation architectures for highly stressed rotating energy systems.

Results of this Preliminary Study

1. Roebel Coil – Initial Testing Done on Original Parts

The testing started by confirming that the partial discharge system without sample was "PD free" (i.e., <0.1 picoCoulomb – noise limit noted as 0.05 – 0.08 pico Coulomb) at 60 Hz AC to the low voltage upper voltage range of 6 kVAC. The sample was then inserted into the circuit and the ac voltage slowly raised. The earth was connected to the outer screen and the high voltage to the end of the tinned wire.

Test 1:
The corona inception voltage (CIV) was at 2.0 kVAC with sparse PD at about 10 – 50 pC levels. The voltage was raised to 2.5 kV where uniform PD's were seen – essentially a steady corona current of <100 microamps.
-checked for contact resistance: visible discharges seen near wire ends. Added mechanical clamp to ensure all wire ends electrically interconnected.

Test 2:
CIV = 1.5 kV for first PD's, 3 kV for continuous corona and audible acoustic noise at PD levels of > 1000 pC per pulse. Voltage raised to breakdown at 3.5 kV. Repeating CIV = 1 kV at which breakdown again found; repeated several times.

A modified Slaughter AC/DC insulation tester was used to confirm AC breakdown of 1.7 kVAC (100 microamps); at 1 kVAC was 20 microamps, and DC breakdown of 2.4 kVDC. The increased AC breakdown is likely a result of allowing the sample to cool during discussions of the PD result meaning so that direct comparison is not necessarily valid.

2-May-98	**Roebel Coil**	
Inception Voltage AC		1.5kV
SS discharges 1000pC/pulse		3.5kV
Slaughter test AC		1.7kV
DC		2.4kV

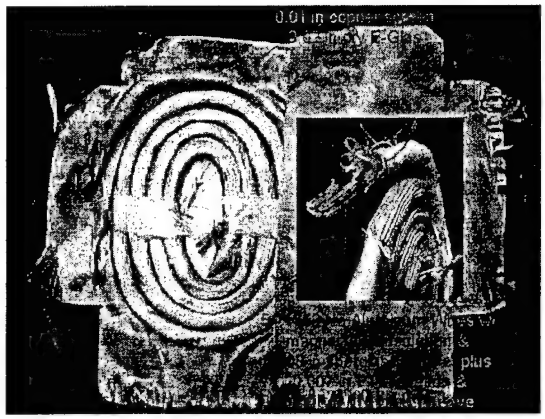

Figure 1. Roebel Coil

Preliminary Conclusions Are As Follows:

1. PD sensitivity of 0.1 picoCoulomb AC is preserved when the test sample is placed in the circuit.

2. Significant heating of the sample was found when at the PD regime of > 1000 picoCoulombs per pulse "corona current steady" level. This meaning that "2V + 1000" volt withstand test is valid ONLY if no significant PD's occur at that voltage test level, otherwise most of the sample life will be used up during the overvoltage test. In present testing, voltages were applied for up to 60 seconds, typical of accepted practice for withstand test times.

Note that none of the withstand tests as advocated today have ANYTHING to do with validating cycle-life; they are ALL UL approved "safety tests" to confirm likelihood of bypass filters on AC mains tolerating expected line transients. In addition, for voltages above about 440 VAC 3-phase, far more strict upper test voltage limits are employed by the utilities for the protection of switchgear and loads during line lightning transients and/or multifrequency simultaneous breaker opening. For example, the work of Greenwood shows transients in two-frequency circuits may reach 8 times the line rated voltage. The conclusion to all this discussion is that transient over voltage (TOV) testing is a safety test only.

In order to design in reliability, the work of Bagirov clearly has shown that the approach must be to operate at a PD threshold below that of electro-chemical degradation. In recent testing on ceramics, the French have shown activity in the few picoCoulomb levels, similar to the results of Bagirov, of PD is at the start of degradation of the insulation system. For each specific insulation architecture and material suite, a PD signature assessment of motorettes you are planning to fabricate would be the most logical approach to identification of aging thresholds.

The ESI facility will be maintained for your continued testing of motorettes, with the note that personnel will be at conferences during the middle of June and not available.

It is strongly recommended that 1 inch diameter aluminum corona balls be attached to the wire ends, via a set-screw.

Thermal PD levels of activity at operational temperature can be assessed later in the summer, using a new hotplate system under development. In addition, it is recommended that two of the AVO-Biddle acoustic PD detectors be acquired immediately and assessed for applicability to in-situ PD measurement during assembly of the next generation ETM compulsator. Calibration of these detectors has not even been attempted but should be feasible utilizing the motorettes under development by CEM and PD testing at ESI. The AVO-Biddle acoustic PD detectors are about \$5 k each and two are needed to record signature in both planes of the sample. Assessment of this approach could start in July. Note that, if successful, this is far more cost effective than acquiring another research AC + DC Biddle PD unit at the ESI; the cost would be at least \$250 k and delivery about 18 months, if indeed there is any interest in the company supplying another unit as they lost significant monies on the first research unit.

2. Multi-Coil Cylinder – Preliminary Partial Discharge Test Results

The testing started by confirming that the partial discharge (PD) system without sample was "PD free"(i.e., < 0.1 picoCoulomb – noise limit noted as 0.05 – 0.08 picoCoulomb under 60 Hz AC excitation) to the "low voltage" range upper voltage limit of 6 kVAC.

The sample was then inserted into the circuit, attaching one coil at a time to the electrode with duct tape, and the earth wire to the PD system earth connection.

Test 1: #6 coil
The corona inception voltage (CIV) was at 0.8 kVAC with fractions of pC at a few peaks. The voltage was raised to 1.0 kVAC where a porch effect was seen as the voltage was further increased- essentially no change in PD with increasing voltage, and PD activity levels were several hundreds of pC per pulse. After aging the sample for a minute at 1.0 kVAC, the CIV was 0.9 kVAC and the corona extinction voltage (CEV) was 0.7 kVAC.

When asked about the sample's ratings, it was agreed that 3 kVDC (theoretical rating) was about 0.8 kVAC (experimental rating); although this must be validated in direct experiments. The DC capability of this research PD machine is planned to be operational about December of this year. The difficulties lay in finishing the design aspects and implementation challenges because of the space charge injection effects that will be seen in the presence of the DC. In itself this is a research program issue and may delay successful operation.

Test 2: #5 coil
The initial CIV for this example was 1.3 kVAC with PD at the 0.2-0.5 pC levels. The initial CEV was measured at 1.1 kVAC. A porch effect was observed at 1.5 kVAC at the 1 – 10 pC level. A series of 7 tests were run to check the CIV and CEV. The CIV only varied slightly between 1.5 – 1.6 kVAC, while the CEV did not vary at all from 1.4 kVAC. After the 7 tests, the voltage was increased to 2.7 kVAC where significant PD activity was observed to >100 pC/pulse. This voltage was held for a minute to observe any change in the CIV & CEV. After this aging was done the CIV was 1.7 kVAC, and the CEV was 1.5 kVAC. The voltage was then increased to 3.3 kVAC to age the sample again, at this voltage the PD was >> 100 pC/pulse. After a minute of aging at this voltage a porch effect was then observed between 1.7 – 1.8 kVAC with PD at the 5 pC level.

The #5 coil will be seen as the exception to the others.

Test 3: #4 coil
The initial CIV for this sample was 1.0 kVAC with a few burst pulses at 1.2 kVAC and many burst pulses at 1.6 kVAC. The CIV increased with successive tests up to 1.4 kVAC as did the CEV to 1.0 kVAC. The final values were measured after a porch effect was observed at 2.0 kVAC and aged for a minute at that voltage.

Test 4: #3 coil
The initial CIV was 1.2 kVAC and the initial CEV was 1.1 kVAC. After a porch effect was observed at 1.2 kVAC and aged the CIV was 1.0 kVAC and the CEV 0.9 kVAC. Once a big porch effect was observed at 2.8 kVAC and aged, the CIV was 1.0 kVAC and the CEV was 0.9 kVAC.

Test 5: #2 coil
The initial CIV was 0.6 kVAC and remained constant. The CEV was observed between 0.3 & 0.4 kVAC. The voltage was increased up to 3.0 kVAC and no porch effect was observed.

Dr. Marinos observed a CIV between 0.8 & 0.9 kVAC and a CEV at 0.7 kVAC with a porch effect at 2.2 kVAC.
Jason Buneo observed a CIV at 0.8 kVAC and a CEV at 0.7 kVAC with a porch effect at 2.0 kVAC.

The last coil #1 will remain untested until the sample is returned to ESI after stress test are employed by CEM/UTA. Initially the observation of the lack of fuzz at the 0.2 pC/pulse resolution indicated the high quality of the impregnate.

1-Jun-98	**Multi-coil cylinder**
#6 coil	
Inception voltage AC	0.8kV
Porch effect	1.0kV
Extinction voltage AC	0.7kV
#5 coil	
Inception voltage AC	1.5-1.6kV
Extinction voltage AC	1.4kV
#4 coil	
Inception voltage AC	1.4kV
Extinction voltage AC	1.0kV
#3 coil	
Inception voltage AC	1.2kV
Extinction voltage AC	0.9kV
#2 coil	
Inception voltage AC	0.8kV
Extinction voltage AC	0.7kV

Preliminary Conclusions Are As Follows:

1. Variations in test results between coils poses the question of consistency in manufacturing.
2. Increasing the test voltage above the inception voltage has varying effects on the coils, potentially the added voltage is deteriorating the sample in some cases and clearing out defects in others.
3. The test results do not illustrate a clear conclusion of the failure mechanism, other than that it would barely pass the design voltage requirement.

3. Braided Wire Samples – Change in Wire Used

Braided wire samples tabulated below:

30-Nov-98 **Braided wire testing w/ ball threaded end fittings**
Open Air testing, no ground attached

Sample #1

Inception voltage AC		none at 20kV
Inception voltage DC w/ AC@20kV		7kV
removed ball end	Inception voltage AC	10.7kV
	Extinction voltage	10.5kV

Sample #16
No Inception voltage up to 20kVAC +18kVDC

Sample #10
Intermittent discharges at 20kVAC +16.3kVDC

Sample #7
Intermittent discharges at 20kVAC + 11kVDC

Sample #17

Inception voltage AC	18.5kV	(fine broken wire)
Extinction voltage AC	17.8kV	

Sample #14
Intermittent discharges at 20kvAC + 10.1kVDC

Sample #9
Intermittent discharges at 20kvAC + 15kVDC

Sample #5
Intermittent discharges at 20kvAC + 11.5kVDC

Sample #8
Inception voltage AC 15.8kV
Large pulses @ 10kVAC +17.4kVDC

Sample #3

Inception voltage	20kVAC + 14.6kVDC
Extinction voltage	20kVAC + 14.5kVDC

Sample #2
Pulses at 8.9kVAC + 8.6kVDC

Sample #4
Intermittent discharges at 10kvAC + 16kVDC

Sample #6

Inception voltage	20kvAC + 7.7kVDC
Extinction voltage	20kVAC + 5.5kVDC
Ground plane attached testing with hot plate	

Sample #14

Inception voltage AC @ room temp	1.5kV
Extinction voltage	~1.5kV
Inception voltage AC @ 130° C	1.3kV
Extinction voltage	1.2kV
Inception voltage AC @ 204° C	1.1kV
Extinction voltage	0.9kV
Inception voltage AC @ 150° C	1.3kV
Extinction voltage	1.2kV
Inception voltage AC @ 88° C	1.3kV
Extinction voltage	1.2kV
Inception voltage AC @ 60° C	1.5kV
Extinction voltage	1.25kV

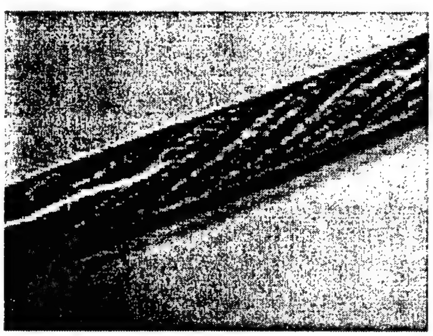

Figure 2

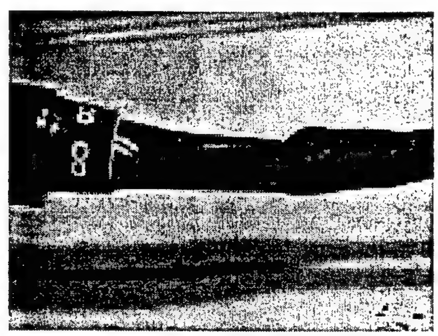

Figure 3

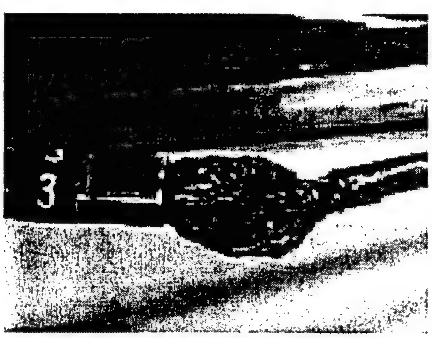

Figure 4

Preliminary Conclusions Are As Follows:

1. The main limitation of the testing was the connectors that were crimped on the ends of the samples.

2. It is highly possible that the results represented discharges at sharp edges, and not the effectiveness of the wire insulation.

3. More representative motorettes are needed to evaluate the design and to avoid introducing field stresses that will not be in the finished product.

4. Encapsulated Wire Samples – Attempts at Improving Connector Challenges

The testing done was in response to discussions after the last round of testing on 11/30/98. On 11/30/98 the tests were done in an open-air setup, with varying layers of shrink tubing covering the samples. This round of testing took into account the possibility that the crimps or loose strands of wire caused the partial discharges. The samples were encapsulated in the planned epoxy (Emerson Cuming 2651MM/ Catalyst 11), bonded to a piece of FEP roll and a titanium groundplane.

This round of testing began on 1/30/99. However due to a blown resistor, testing had to be put off until 2/6/99. The setup for these tests was changed due to the added weight of the samples. The picture following illustrates the setup, the hot plate (unplugged & room temperature) was placed in the Biddle and a testing arm was used on the sample with spherical electrodes on both ends. The ground of the hotplate was attached to the Biddle ground.

The tests were done up to the needed voltage on DC of 6 kV, all samples passed. None of the samples passed the DC + AC test for the needed voltages of 6 kV DC + 8 kV AC.

Sample #17
DC test @ 6 kV – No P.D. Activity.
Inception voltage 6 kV DC + 2.8 kV AC trical pulses

Sample # 10
DC test @ 6 kV – No P.D. Activity.
Inception voltage 6 kV DC + 3.6 kV AC PDIV
Extinction voltage 6 kV DC + 3.3 kV AC PDEV

Sample # 7
DC test @ 6 kV – No P.D. Activity.
Inception voltage 6 kV DC + 3.7 kV AC PDIV
Extinction voltage 6 kV DC + 3.4 kV AC PDEV

Sample #1
DC test @ 6 kV DC – No P.D. Activity.
6 kV DC + 3.8 kV AC PDIV
6 kV DC + 3.4 kV AC PDEV

Note: Sample #9 & 16 are wrapped together and flared out at the ends, however the sample does not have the piece of FEP roll and groundplane bonded to it.

Sample # 9 with 16
DC test @ 6 kV – No P.D. Activity.
Inception voltage 6 kV DC + 7.2 kV AC PDIV
Extinction voltage 6 kV DC + 6.3 kV AC PDEV
tested both electrodes

Sample # 16 with 9
DC test @ 6 kV – No P.D. Activity.
Inception voltage 6 kV DC + 5.8 kV AC PDIV
Extinction voltage 6 kV DC + 5.1 kV AC PDEV

Note: Sample # 9 & 16 had the best results, and it did not have a groundplane bonded to it.
At this point a test was done to see if the sharp edge of the FEP roll may have caused the partial discharges. Sample #7 was used to tape back the ends of the FEP roll and groundplane to create a radius instead of a sharp edge. It was then placed back in the test setup.
DC test @ 6 kV – No P.D. Activity.
Inception voltage 6 kV DC + 5.4 kV AC PDIV
Extinction voltage 6 kV DC + 4.4 kV AC PDEV
This shows almost 2 kV higher than the first test this round of sample #7
The only sample tested on a cold hotplate on 11/30/98 was sample #14 and it had an inception and extinction voltage of 1.5 kV AC

Below, in Figure 5, is the Motorette on the heating substrate. Grounding metallized plastic sheet glued to the potted winding section is clearly visible in the larger figure.

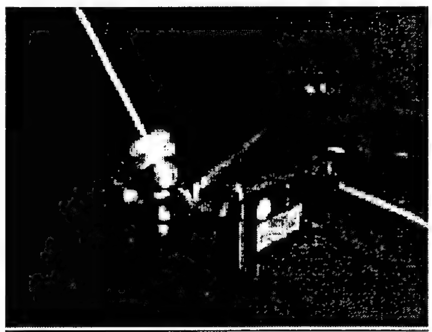

Figure 5

Below, in Figure 6, is the Motorette showing the metallized film ground plane bent back to reduce field enhancement at the ends. The grounding metallized plastic sheet glued to the potted winding section is clearly visible in the larger figure.

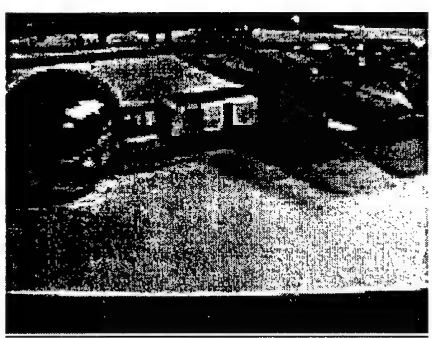

Figure 6

Below is Figure 7, the Motorette showing the cross-sectioned winding. . Cavities in the impregnated Insulation System are clearly visible in the larger figure, near the center.

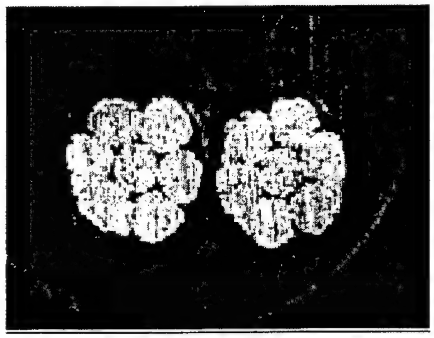

Figure 7

Below, in Figure 8, is the Motorette showing the larger magnification of the cross-sectioned winding.

Figure 8

Preliminary Conclusions Are As Follows:

1. The revised motorettes may still introduce field stresses not seen in the finished stator. The groundplane that is attached has sharp edges close to the ends of the motorettes. By creating a radiused curve at the ends, the test result greatly improved.

2. The epoxy used was planned to hold the wires in place, and not to be used as increased insulation. However voids in the epoxy can still cause higher field stresses and increase the chance of premature failure.

3. It should also be noted that the motorette that did not have a simulated attached groundplane illustrated the best result.

5. DV/Dt and 2 Wire Sample – Repetition Rate Experiments

Sample # 7 was used in this experiment. The sample was modified during the last partial discharge testing by taping back the ends of the FEP roll to create a radius instead of a sharp edge. The figure below illustrates the test set-up on the MIT Model 9 Hard Tube Pulser (MOD-9). One end of the sample was placed on the brass electrode of the output and held in place with some tape. The sample rested on an insulator, with a clip lead attaching the groundplane to the system ground.

The test started off with a rise time of 50 nanoseconds. With fine-tuning, to maximize the rise time while minimizing the grid voltage, the output waveform was clearest with a 60 nanosecond rise time. Without knowing the actual performance specifications as far as rise time with the finished product, this experiment used 60 nanoseconds.

The experiment ran at 1 kV for about five minutes and then was increased to 5 kV for approximately fifteen minutes. A square wave generator at 1 kHz generated the pulse. Finally we increased the voltage to 10 kV, which is approximately 167 kV/μsec without any problems. This initial test does not measure PDIV and PDEV, this does show that the sample did not breakdown from applying voltage at the above stated rate.

Below is Figure 9, the Motorette showing the test setup of the dV/dt testing with the MOD-9.

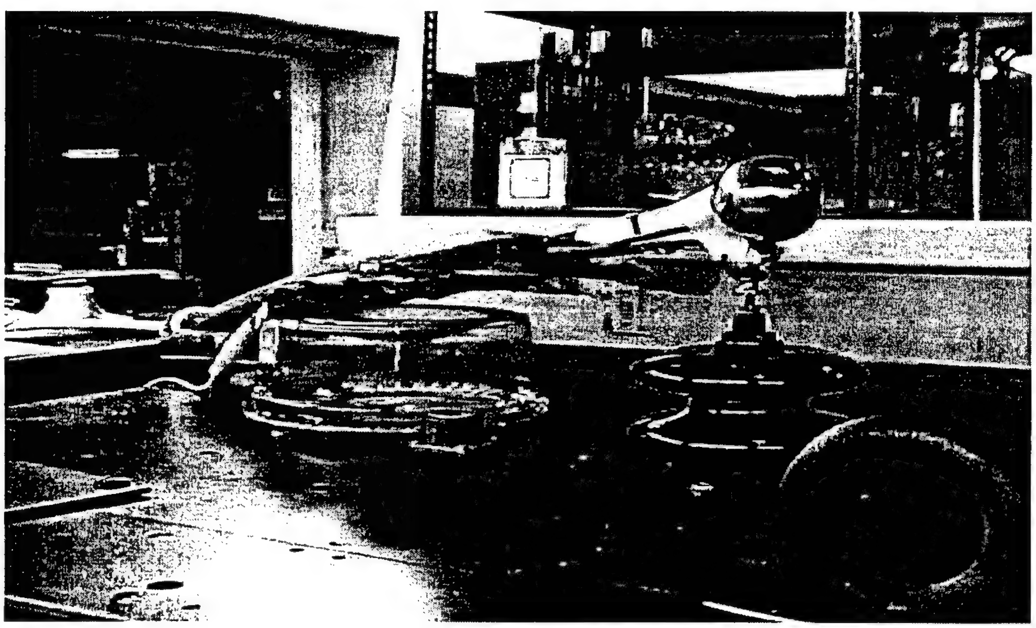

Figure 9. Test set-up of sample on Mod – 9

Figures 10 and 11 are pictures of the oscilloscope showing the rise time and the pulse width.

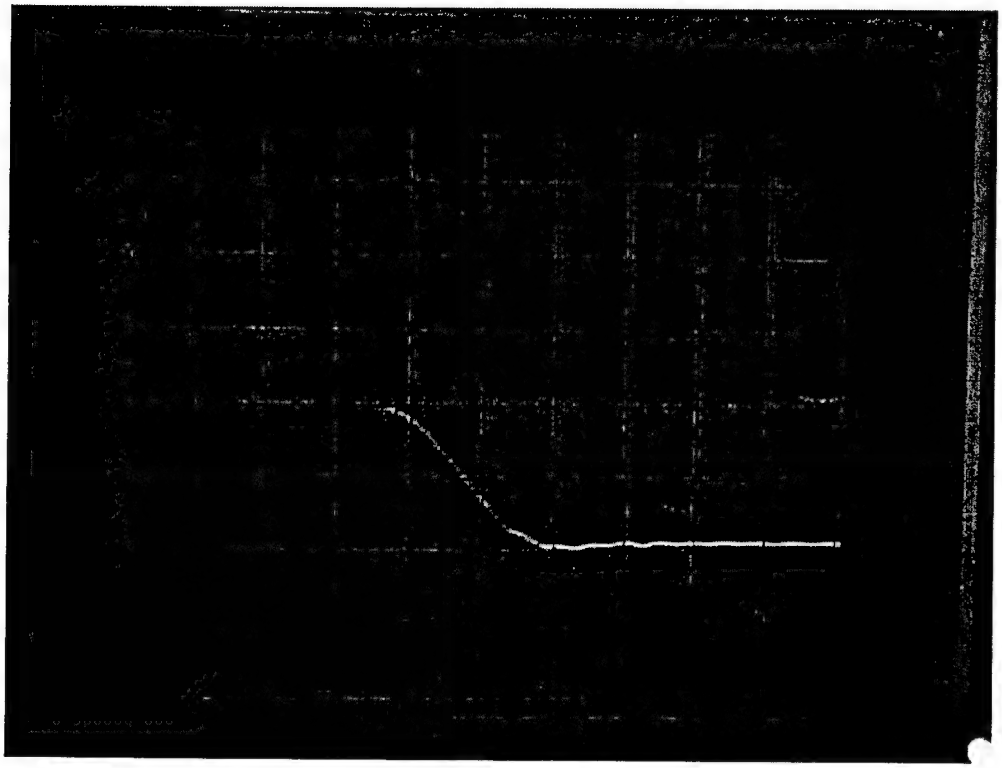

Figure 10. Pulse rise time of sample 5 kV/div, .05 μsec/div

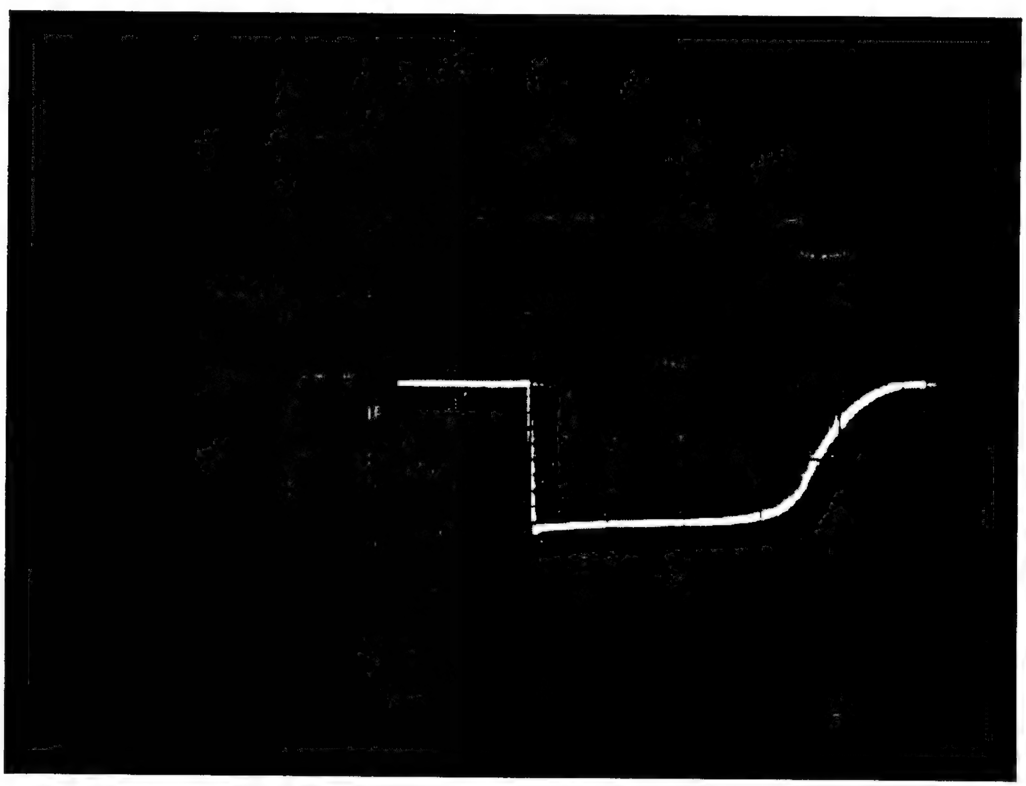

Figure 11. Pulse width of sample 5kV/div, 1μsec/div

22-Mar-99	**DV/DT testing**
Sample#7	
No breakdown at	10kV;60ns turn-on time; 1kHz frequency

27-Mar-99	**Biddle testing**
HV on #9	
Inception voltage AC	4.1kV
Extinction voltage	3.5kV
HV on #16	
Inception voltage AC	6.9kV
Extinction voltage	6.2kV
HV on #16/Ground on #9	
DC test @ 8kV No P.D. Activity.	
Inception voltage AC	2.1kV
Extinction voltage	1.8kV

Preliminary Conclusions Are As Follows:

1. The dV/dt test only shows that the motorette did not fail, the MOD-9 does not have in-situ partial discharge analysis.

2. The AC test done with the motorette in which two wires are close to each other, illustrate some differences in manufacturing the part, possibly due to voids or sharp edges close to the electrodes.

3. The DC test illustrates that the FEP around the wires is sufficient insulation to avoid failure from space charge.

6. Stator Testing – Final Testing of the Total Stator

The final stator was shipped and tested at the ESI's facility. The first potential area for skewed results were the numerous thermocouple wires throughout the stator for other tests. This prompted some additional tests with a previous motorette.

20-Aug-99 **Finished Stator**

Test #1 All phases to ground

Inception Voltage AC	2.8kV
Inception Voltage DC	6kV

21-Aug-99 **Thermocouple testing**

Test #2 Thermocouples(TC) tied together w/1Mohm

HV on TC/phases to ground

Inception voltage AC	1.8kV
Extinction voltage	1.3kV

HV on phases/TC to ground

Inception voltage AC	1.8kV
Extinction voltage	1.1kV

DC test @ 6kV No P.D. Activity.

Inception voltage	6kVDC +1.8kVAC
Extinction voltage	6kVDC +1.1kVAC

HV on TC only

Inception voltage AC	17.5kV
Extinction voltage	17kV

Sample#10

Inception voltage AC	2.9kV
Extinction voltage	2.7kV

Sample#10 w/ TC epoxied to sample

HV on sample/TC to ground

Inception voltage AC	1.3kV
Extinction voltage	1.1kV

HV on sample/TC NOT grounded

Inception voltage AC	3kV
Extinction voltage	2.8kV

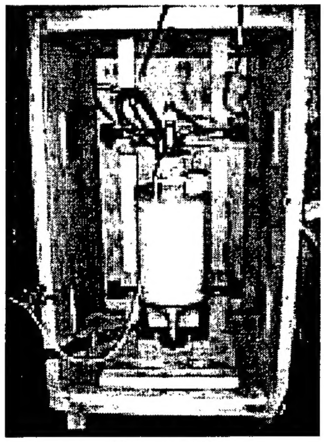

Figure 12

Stator test setup

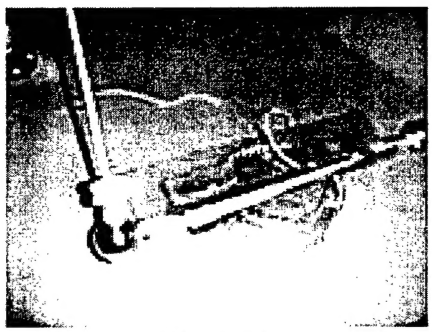

Figure 13

Figures 12 and 13: Thermocouple experiment setup with motorette to evaluate the effects of the latter on PD activity of the complete motorette.

Preliminary Conclusions Are As Follows:

1. The DC test was sufficient for the design criteria.

2. The AC test was low, suspect to the thermocouple wires throughout the stator.

3. After follow up tests with a motorette to study the effect of having NO thermocouple wiring, electrothermal aging experiments are needed to develop cycle-life engineering design guidelines.

Conclusions from this Research

The highlights of the conclusions are:

1. **Computer modeling to help with electric field control: maximize field uniformity**

2. **Look at viscosity in epoxy to avoid cavities in encapsulated insulation systems**

3. **Look at the thermal coefficient of expansion and modulus of strength to reduce stress**

Tests run to date at the ESI were preliminary efforts. Before any more testing and diagnostics are carried out, more representative motorettes need to be designed so that it is as close as possible to the finished product. Of specific interest is the accurate representation of the groundplane as it applies to the stator. Modeling of the geometries involved will not be insignificant, but with the cooperation of CEM's modeling experts with ESI's, a sound motorette can be designed on for future experiments.

Additional testing with the existing motorettes in air would not provide any useful data because the failure mechanisms of most of the tests stem from poor connectors and or ground plane design. During further work, evaluation of motorette behavior in fluid environments, as in the designed machine, is what really needs to be done in order to develop cycle-life engineering design guidelines.

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